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A new method to determine the required impact toughness for petroleum drill pipe used in critical sour environment

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Abstract

This paper presents a new model to determine the required impact toughness of petroleum drill pipe steel based upon leak-before-break fracture principle. The loss law of impact toughness in sour critical environment was also experimentally measured which could act as a good supplement for Leak-Before-Break fracture principle. The dominating products were experimentally measured to determine the current industrial ability. The results showed that the required impact toughness through above model could be fully realized now.

Keywords:Impact toughness, drill pipe steel, leak-before-break, sour environment;

1. Introduction

The west oil & gas field in China including SICHUAN, CHONGQING and XINJIANG districts has became an important exploitation target now. One key feature there is obvious existence of corrosive hydrogen sulfide medium. For example, more than 70 percent fields contain high hydrogen sulfide medium and the highest content reaches 92 percent in weight in SICHUAN and CHONGQING districts. The sulfide stress corrosion crack (as called SSCC) for drill pipe frequently occurred due to absence of applicable guiding regulation, which has caused huge economic damage and environmental contamination [1, 2]. Statistical data showed that the average loss is 100 thousand US dollar for one accident due to SSCC failure of drill pipe [3]. In 1995 more than 10 million RMB losses had been caused by once SSCC failure of drill

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pipe in SICHUAN DU-1 well. So there is obvious safety risk when drilling in these gas fields and applicable specification for drill pipe used in sour regions was very necessary and urgent.

In 2001, Alberta drilling and completing committee of Canada proposed the "Industry Recommended Practices For Critical Sour Environment Of Drill String Design" (IRP1.8 and IRP6.3), regarding conventional drilling and underbalanced drilling processes, which provided initial technical specification for anti-sulfur drill pipe [4, 5]. However this cannot prevent drill pipe's SSCC failure even though the supplied drill pipe can meet its requirements better. And so a new regulation for drill pipe was required urgently. This paper will present a new method to determine the required impact toughness value for petroleum drill pipe in critical sour drilling environment.

2. Failure Modes of Drill Pipe

Break and leak are two major failure modes for drill pipe as shown in Fig 1. During the drilling process drill pipe bears a periodic fatigue load due to centrifugal effect of drill string. It is well known that break failure is mainly due to fatigue load. In fact, the leak failure also results from fatigue load. Fig.1 shows a large number of drill pipe leaking cases and there is obvious fatigue propagation morphology at both ends of leaked hole accompanying the leaking process and so fatigue is also the nature of leak mode [6].

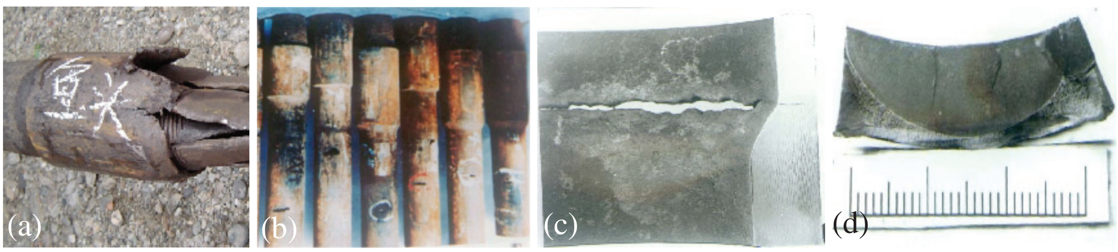

Fig.1 The fatigue nature of drill pipe leak failure (a) break failure mode (b)leak failure mode (c) leaked hole and crack (d) fatigue growth morphology

3. Model to Determine Impact Toughness of Drill Pipe in Critical Sour Environment

The break failure of drill pipe consequentially leads to rupture of drilling string and fish salvage, which will cause huge economic cost, environmental contamination and even serious casualties due to blowout of hydrogen sulfide. While the leak failure can be detected by monitoring the pressure changes of drilling mud, and the leaked drill pipe will be replaced in time. Therefore, leak failure should be accepted while break should be avoided which was called Leak-Before-Break (LBB) fracture principle [3].

3.1. LBB model

Statistical data of leaked drill pipe indicate that the leading hole is elliptical form in geometry morphology as shown in Fig.1. The maximum crack length is 50mm, and minimum is 7mm. More than 80% leaked holes have a length between 20 mm to 40 mm [7]. So the length of 40 mm should act as the critical cracking size in building LBB model, as shown in Fig.2. Broadly drill pipe belong to cylindrical pressure vessel and the stress intensity factor expression is shown as Eq.1 [8]. When leaking occurs, fatigue crack propagates through the whole pipe wall in thickness direction and the corresponding value of stress intensity factor is the critical fracture toughness.

$$K_I = \sigma_t \sqrt{\pi R \theta} F_t (R/t, \theta/\pi) \tag{1}$$

Where σ_t is the tensile stress at crack tip, R is the equivalent radius of drill pipe, θ is half of crack angle, t is the wall thickness and F_t is the shape factor related with diameter and wall thickness of drill pipe.

$$F_t = 1 + A\{5.3303(\theta/\pi)^{1.5} + 18.773(\theta/\pi)^{4.24}\} \tag{2}$$

Where $A = \{0.125(R/t) - 0.25\}^{0.25}$ for 5≤R/t≤10, and $A = \{0.4(R/t) - 3.0\}^{0.25}$ for 10<R/t≤20

Now we can achieve the corresponding impact toughness value of drill pipe with different geometry size according to the relationship between fracture toughness and impact toughness [9], as shown in Eq.3.

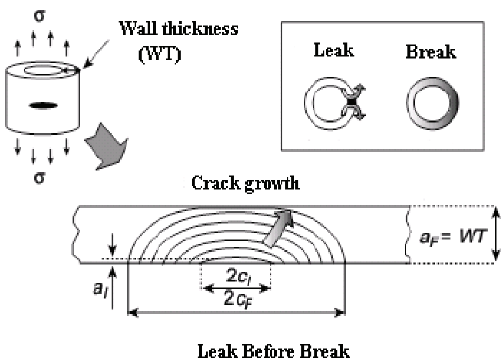

Fig.2 Leak-Before-Break model

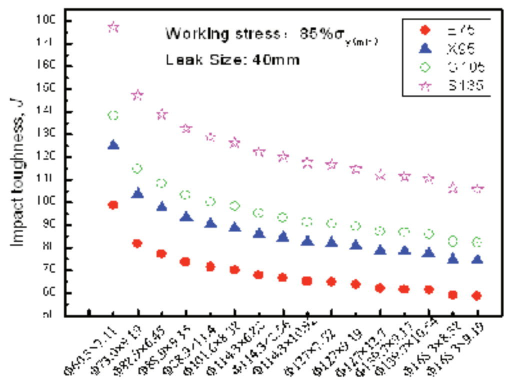

Fig.3 LBB impact toughness requirement for different scale of drill pipe

$$K_{1C} = (0.5172 * CVN * Y - 0.0022Y^2)^{0.5} \tag{3}$$

Where K_{IC} is plane strain fracture toughness of material, *CVN* is the longitudinal absorbed energy of impact sample in 10mm×7.5mm×55mm geometry size, and Y is the yield strength of drill pipe steel.

Uniaxial tensile stress is assumed as working stress here. Tensile stress is perpendicular to crack surface and hence is the maximum principal stress for circumferential surface crack. Considering safety factor of strength design, 85 percent yield strength is adopted as the maximum service stress. Longitudinal impact toughness required by drill pipe with different strength grade can be calculated by Eq.4~Eq.7.

$$CVN = X.\sigma^2 + 2.20 \text{ for E75 grade} \tag{4}$$

$$CVN = X.\sigma^2 + 2.79 \text{ for X95 grade} \tag{5}$$

$$CVN = X.\sigma^2 + 3.08 \text{ for G10grade} \tag{6}$$

$$CVN = X.\sigma^2 + 3.96 \text{ for S135 grade} \tag{7}$$

Where σ is the service stress and *X* is a constant coefficient, which is related with outer diameter and wall thickness of drill pipe and can be achieved through Table 1.

Table 1 Polling list for the coefficient of X, 10^{-4}

Φ, mm	t, mm	S135	G105	X95	E75
60.3	7.11	2.77	3.56	3.93	4.98
73	9.19	2.29	2.94	3.25	4.12
88.9	6.45	2.15	2.76	3.05	3.87
88.9	9.35	2.05	2.64	2.91	3.69
88.9	11.4	1.98	2.56	2.83	3.58
101.6	8.38	1.95	2.51	2.77	3.51
114.3	6.88	1.88	2.43	2.68	3.40
114.3	8.56	1.85	2.38	2.63	3.33
114.3	10.92	1.81	2.32	2.57	3.26
127	7.52	1.80	2.31	2.55	3.23
127	9.19	1.77	2.27	2.51	3.18
127	12.7	1.72	2.22	2.45	3.10
139.7	9.17	1.71	2.20	2.43	3.08
139.7	10.54	1.69	2.18	2.41	3.05
168.3	8.38	1.63	2.09	2.32	2.94
168.3	9.19	1.62	2.08	2.30	2.92

Where Φ is outer diameter, t is wall thickness, and S135, G105, X95, E75 refer to different grades for petroleum drill pipe.

Fig.3 shows the impact toughness value of the full range scale of drill pipe in API Spec 5DP under critical leaking condition according to above model. It should be noted here that the bearing capacity of drill pipe under critical condition, which is the essential factor in drill string design, was not considered in this result.

3.2. Impact Toughness Loss Law in Sour Environment

The impact toughness of drill pipe steel has an obvious lose in sour drilling environment. Experiments for SS105 anti-sulfur drill pipes (except sample B is a general G105 drill pipe) from major manufactures in worldwide scope were done by soaking the samples in solution A for 1~30 days [10], whose results were shown in Fig.4.The results showed that the impact toughness value decreased apparently on first day and then stabilized. This phenomenon means that the residual impact toughness after one day's immersion is the actual effective toughness, which should meet LBB fracture principle. For 7 kinds drill pipe samples, the highest toughness decline is 44J and the minimum is 22J, and the rest decreases about 30J averagely which is an important parameter for drill pipe steel in sour drilling environment, especially in underbalance drilling process. Now a conclusion should be achieved that the impact toughness of drill pipe steel should meet LBB principle and toughness loss requirement simultaneously. Samely take 105ksi-graded drill pipe with 127 mm diameter and 9.19 mm wall thickness as example, we can see that the impact toughness requirement of 120 J is also able to be realized according the currently industrial ability, which is shown in Fig.6.

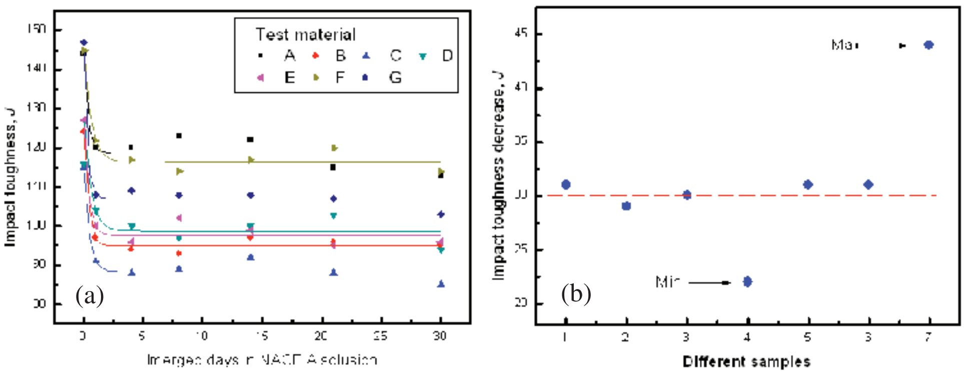

Fig. 4 Impact toughness loss experimental data, (a) impact toughness loss law, (b) statistical data of impact toughness loss.

4. Statistical analysis for industrial products

Take drill pipe of 127mm outer diameter, 9.19mm wall thickness for example, the requirement of impact toughness is shown in Fig.5.Because the cylindrical model here has considered outer diameter, wall thickness and curvature effect of drill pipe, the calculation result of impact toughness is higher than Szklarz's model [3].

Fig.6 presents the statistical analysis of impact toughness from different 105ksi-graded drill pipe manufactures with 127mm diameter and 9.19 wall thickness, which reveals that the requirement of 90J impact toughness is very easy for G105-graded drill pipe with dimension of 10mm×7.5mm×55mm.

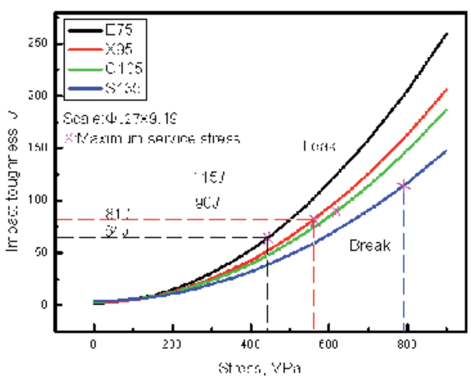

Fig. 5 LBB impact toughness for 5 in drill pipe

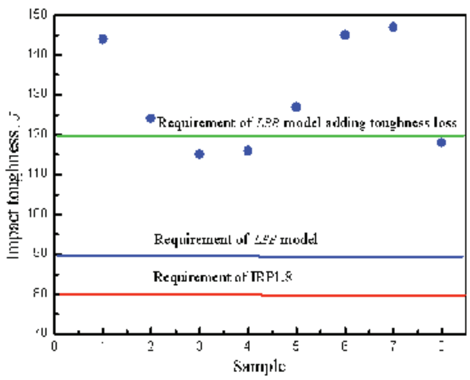

Fig. 6 Statistical data of impact toughness

5. Conclusions

1) The impact toughness value of drill pipe steel for different strength grade was deduced according to Leak-Before-Break fracture principle, which can efficiently prevent drill pipe unexpected cracking, fishing and environmental contaminant due to blowout of hydrogen sulfide medium.
2) The loss law of impact toughness of drill pipe steel in critical sour environment has been achieved through experimental method, which should be considered in sour drilling environment especially for underbalanced drilling process.
3) Impact toughness requirement through the model described here can be fully realized according to current industrial ability.

Acknowledgements

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